# Final Report

**Principal investigator : Prof. Tae Won Kang**

**Title of proposal : Indium Gallium Nitride/Gallium Nitride (InGaN/GaN) Nanorods Supperlattice (SL)**

**Institution : Dongguk University (QSRC)**

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Recently, GaN-based system has gained immense popularity in optoelectronic applications particularly in ultraviolet (UV)-visible region due to it's direct large band gap, high thermal stability, and strong resistance to radiation. One-dimensional nanostructures, such as InGaN/GaN nanorod supperlattice (NRs SL), have attracted much attention because of its potential for novel nanoscale electronic and photonic device applications. These nanorods have been synthesized by various methods such as laser ablation, sublimation, chemical vapor deposition, etc. In conventional growth methods, there exists a large density of dislocations in the GaN-based structures which serve as non-radiative recombination centers, which leads to a degradation in the optoelectronic properties. In order to prevent this kind of degradation, the formation of dislocation-free InGaN/GaN NRs SL embeded in the NR is preferred which have negligible nonradiative recombination loss, and thus the efficiency of light output power will be much higher compared to InGaN/GaN MQW layers. Moreover, the sidewalls of the NR play an important role in extracting the light efficiently. A larger surface area is desirable, since it provides more pathways by which generated photons can escape. Therefore, adoption of NR array (NRA) geometry holds promise for the fabrication of highly efficient LEDs.

Our work demonstrates the realization of high-brightness and high-efficiency LEDs using dislocation-free InGaN/GaN SL NRAs by hydride vapor phase epitaxy (HVPE). The benefits of the InGaN/GaN SL NRA LEDs are examined in this work, and their characteristics are compared to those of conventional broad area(BA) LEDs.

The NRs SL were grown on sapphire substrates by HVPE in the absence of a catalyst, resulting in the growth of vertically well-aligned NRs with homogeneous length and diameter as revealed by the high resolution scanning electron microscope (HR-SEM) image. Structural characterizations of the InGaN/GaN NRs SL by a X-ray diffraction and transmission electron microscopy indicate that the NRs are preferentially oriented in the c-axis direction. The optical properties of dislocation-free NRs SL were studied by photoluminescence (PL), PL excitation, and time-resolved PL spectroscopy.

The InGaN/GaN NRs SL prepared in this study consist of a six-period $In_{0.25}Ga_{0.75}N$/GaN (4.8 nm/12 nm) on n-type GaN NRs. A cross-sectional-view SEM image of the NRs SL is shown in Figure 1A. Figure 1B is a 30$^{o}$. tilt-view HR-SEM image, revealing that the NRs SL are well-aligned vertically, with

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14. ABSTRACT
**This work demonstrates realization of high-brightness and high-efficiency LEDs using dislocation-free InGaN/GaN SL Nano rods arrays (NRAs) by hydride vapor phase epitaxy (HVPE). The benefits of the InGaN/GaN SL NRA LEDs are examined in this work, and their characteristics are compared to those of conventional broad area (BA) LEDs.**

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homogeneous lengths and diameter (around middle point distributions)[1]. Typical mean diameter was in the range of 70-90 nm around the middle point (p-n junction with InGaN/GaN NRs SL) of NR and length was in the range of 1-1.2 μm, respectively. Intervals between NRs were sufficiently wide, as shown in Figure 1B. Figure 1C and its inset show the TEM image and the corresponding selective area electron diffraction (SAED) pattern of the middle area of the $In_{0.25}Ga_{0.75}N$ /GaN NRs SL. Figure 1C exhibits dark and bright layers in the SL. Dark regions designate $In_{0.25}Ga_{0.75}N$ layers, and bright regions correspond to GaN layers. The interfaces between the different layers were clearly visible. The NRs SL grown along the c-axis of the hexagonal crystal structure were dislocation-free. The interfaces between $In_{0.25}Ga_{0.75}N$ and GaN were as defect free as that of the GaN layer, and interface dislocations are not observed. In the inset of Figure 1C, the [0001] direction was parallel to the long axis of rod, indicating that the [0001] direction is a common growth direction of NR. The SAED pattern of the same NR from the [2110] direction confirmed that it was a single crystal.

Figure 2A shows the temperature dependent PL spectra of the InGaN/GaN SL NRAs. A strong emission peak at 477 nm is clearly observed at 15 K[2]. The main blue-light-emission remained bright even at room temperature, and the integrated PL intensity is reduced only by a factor of about 1.8 with increasing temperature from 15 to 300 K. Therefore, the integrated PL intensity ratio of 300 to 15 K ($I_{300\,K}$ / $I_{15\,K}$) is 55.4%, which can be considered as $\eta_{int}$ by assuming the efficiency at 15 K to be 100%. This assumption is quite reasonable in our PL data as the constant integrated PL intensity was observed in the temperature range of 15 to 50 K, which indicates almost no influence of non-radiative processes in PL at 15 K. Figure 2B shows the Arrhenius plot of the integrated PL intensity obtained from the main emission over the temperature range from 15 to 300 K. The best fitting gives two activation energies of about 16.3 and 171.1 meV. The small activation energy of 16.3 meV can be attributed to the exciton binding energy due to some impurities. The main quenching process of the sample is related to the thermal escape of carriers out of confining potential with the large activation energy of 171.1 meV correlated with the depth of the confining potential. It is worth noting that this activation energy value is much larger than those reported in literature for BA InGaN MQWs. Since the thermal activation energy obtained for BA InGaN MQWs have been much smaller than the band-offset and bandgap energy difference between the wells and the barriers, it has been attributed to the thermal barrier escape from localized states and/or to the capture at non-radiative centers inside the InGaN wells. Therefore, extraction efficiency and internal quantum efficiency are increased significantly, due to the large sidewall surface area and dislocation-free characteristics of our SL NRA LEDs. Although the total active volume is reduced, the enhancement in both extraction and internal quantum efficiencies gives the SL NRA LEDs an advantage in the overall external quantum efficiency over the conventional BA LED.

Carrier transportation in the NRA LEDs is physically confined to the vertical direction due to the geometry of the one-dimensional structure [3,4]. Similar factors apply in case of the microring LEDs, which have larger contact areas than that of the SL NRA LEDs. The inset of Figure 3A depicts the current-voltage (I-V) behavior of a six-period InGaN/GaN SL NR LED measured at room temperature. The carrier concentrations of the n- and p-type NR regions were about $1 \times 10^{18}$ $cm^{-3}$ and about $5 \times 10^{17}$ $cm^{-3}$ , respectively. The n- and p-type electrodes of single NR p-n junctions were fabricated using focused ion beams. The slightly higher threshold voltages in SL NRA LEDs can also be attributed to the effective contact area of the p-type GaN NR in the devices. A green curve represents the I-*V* behavior of the single InGaN/GaN SL NR p-n junction. I-*V* measurements showed rectifying behavior consistent with the presence of the NR p-n junction with a turn-on voltage of about 1.5 V in forward bias. I-*V* measurements of NR p-n structures exhibit a clear current rectification in NR transport. Figure 3B shows the light output power versus forward current (L-I) for the InGaN/GaN SL NRA LEDs and for the conventional BA LEDs measured from the top of the samples. The inset of Figure 3B shows a photograph image taken from the top of the SL NRA LEDs under a biased condition of about 20 mA. The actual total output power of this LED should be much higher than the measured value shown here since most of the light emitted from these LEDs was not collected. This was unavoidable, due to the extremely small area ($1 \times 1$ $mm^2$ ) of the detector. An important result, shown in Figure 3B, is that the light power output of SL NRA LEDs is significantly higher than that of the output of conventional BA LEDs. At an injection dc current of 20 mA, the SL NRA LEDs emit about 4.3 times more light than the conventional BA LED, providing solid evidence that the sidewalls facilitate light extraction. This can be attributed to the presence of a large sidewall surface area for light extraction, as in microdisk and microring LEDs. It is well recognized that extraction efficiency is only a few percent in conventional BA LEDs owing to the total internal reflection occurring at the LED/air interface. It is quite clear that the generated light can come out of SL NRA LEDs very easily than in conventional BA LEDs. It is thus expected that extraction efficiency should be significantly higher in SL NRA LEDs.

Our results demonstrate the realization of the high-brightness and high-efficiency LEDs using dislocation-free InGaN/GaN SL NRAs by HVPE. The SL NRA LEDs have similar electrical characteristics as conventional BA LEDs. However, due to the lack of dislocations and the large surface areas provided by the sidewalls of NRs, both internal and extraction efficiencies are significantly enhanced. At 20 mA dc current, the SL NRA LEDs emit about 4.3 times more light than the conventional BA LEDs, even though overall active volume of the SL NRA LEDs is much smaller than conventional LEDs. Moreover, the fabrication processes involved in producing SL NRA LEDs are almost the same for conventional BA LEDs. The present method of utilizing dislocation-free SL NRA LEDs is applicable to super-bright white LEDs as well as other semiconductor LEDs for improving total external efficiency and brightness of LEDs. This work was published in Journal of the Korean Physical Society, 45, S701 (2004).

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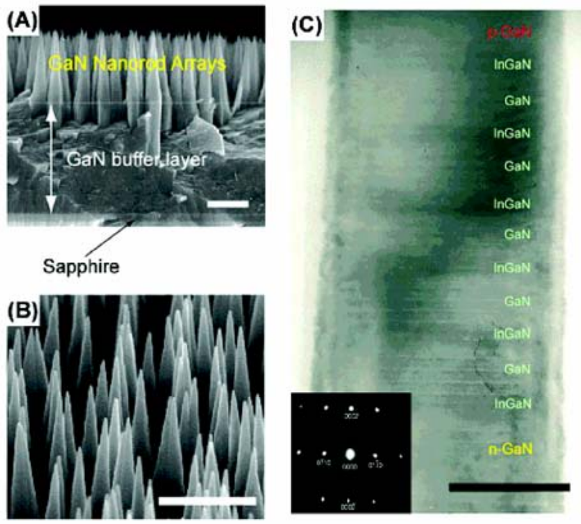


Figure 1. Scanning electron microscope (SEM) and transmission electron microscope (TEM) images of vertically well-aligned InGaN/GaN SL NRAs grown on c-plane sapphire substrate. (A) Cross-section-view SEM image of InGaN/GaN SL NRAs. Scale bar is 500 nm. (B) 30° tilt-view high-resolution scanning electron microscope (HR-SEM) image of InGaN/GaN SL NRAs. InGaN/GaN SL NRs were vertically aligned on the sapphire substrate. Scale bar is 500 nm. (C) TEM image of $In_{0.25}Ga_{0.75}N$ /GaN SL in a NR. The length of NR was about 1 μm and the diameter was about 70 nm around the middle point of the NR. Scale bar is 30 nm. Inset shows the corresponding selective area electron diffraction (SAED) pattern.

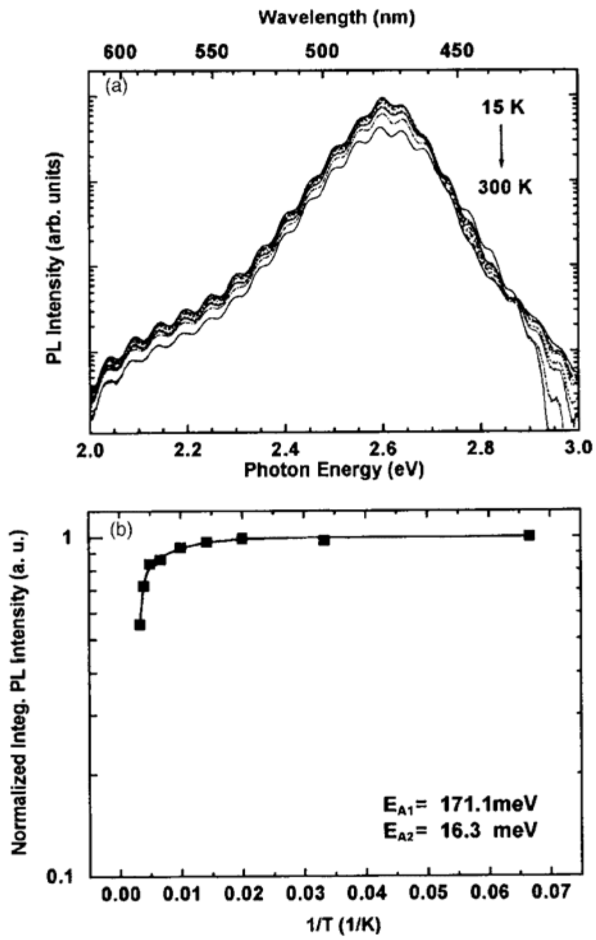


Figure 2. (A) Temperature dependent PL spectra from 15 to 300 K excited by a 325 nm He-Cd laser and (B) the Arrhenius plot for the InGaN/ GaN SL NRA sample.

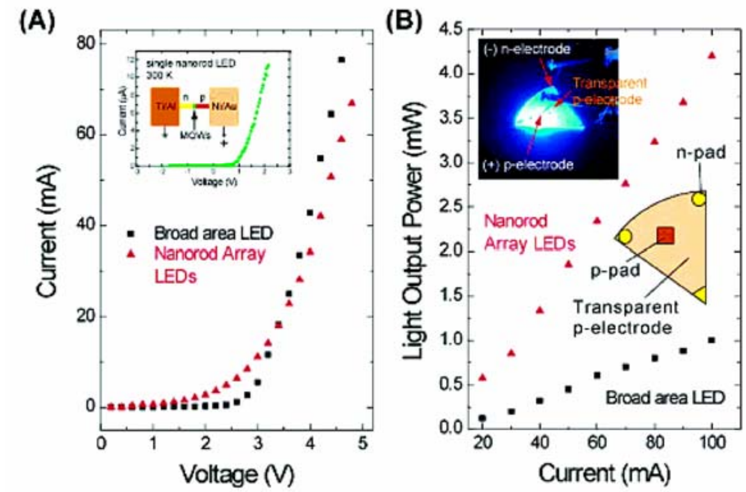


Figure 3. Electrical properties of InGaN/GaN SL NRA LEDs (▲) compared to conventional BA LEDs (■). (A) Current-voltage *(*I-V) characteristics of the SL NRA LEDs and conventional BA LEDs. Insets show the I-*V* characteristics of a single GaN NR p-n junction with a six-period InGaN/GaN SL and a schematic diagram of an InGaN/GaN NRA LED. (B) Light output power-forward current *(*L-I) characteristics of a six-period InGaN/GaN SL NRA LED using an on-wafer testing configuration, as compared to a conventional BA LED. Insets show the top-view photograph image (above) and schematic diagram (below) of a blue emission from $In_{0.25}Ga_{0.75}N$ /GaN SL NRA LEDs at 20 mA dc current.